The fraction of galaxies that contain active nuclei and their accretion rates

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ABSTRACT

We investigate the relationship between the present day optical luminosity function of galaxies and the X–ray luminosity function of Seyfert 1s to determine the fraction of galaxies which host Seyfert 1 nuclei and their Eddington ratios. The local type 1 AGN X–ray luminosity function is well reproduced if $\sim 1\%$ of all galaxies are type 1 Seyferts which have Eddington ratios of $\sim 10^{-3}$. However, in such a model the X–ray luminosity function is completely dominated by AGN in E and S0 galaxies, contrary to the observed mix of Seyfert host galaxies. To obtain a plausible mix of AGN host galaxy morphologies requires that the most massive black holes in E and S0 galaxies accrete with lower Eddington ratios, or have a lower incidence of Seyfert activity, than the central black holes of later type galaxies.

Key words: galaxies:active – galaxies:luminosity function – accretion

1 INTRODUCTION

Accretion onto a massive black hole has remained the standard paradigm for active galactic nuclei (AGN) for several decades (eg Lynden-Bell 1969, Rees 1984). In recent years, a considerable amount of evidence has accumulated for the existence of massive black holes in many, perhaps all, galaxies (Magorrian et al. 1998, Kormendy & Richstone 1995). The connection between the formation and evolution of massive black holes and their host galaxies is currently the subject of great interest and investigation (eg Fabian 1999, Salucci et al. 1999, Cattaneo, Haehnelt and Rees 1999).

The luminosity function of AGN has been used for many years to track the statistical evolution of the AGN population with cosmic epoch, but does not allow distinction between a relatively small population of long lived AGN or many short lived generations of AGN. The Eddington ratio, i.e. the ratio of an object's luminosity to its Eddington luminosity, was proposed to be a powerful discriminator of AGN activity patterns by Cavaliere & Padovani (1988) with long lived AGN having low Eddington ratios ($\sim 10^{-4}$) and short lived AGN having high Eddington ratios (~ 1). In a variety of wavebands, from radio to X–ray, the luminosity function of AGN has a characteristic two-power law shape with a knee dividing the low and high luminosity objects (eg Dunlop & Peacock 1992, Boyle, Shanks & Peterson 1988, Page et al. 1997). It has an obvious resemblance to the luminosity function of galaxies, which is not surprising since AGN are found in galaxies. Only a few attempts have been made to relate the galaxy and AGN luminosity functions, predominantly in the form of models for the joint formation of galaxies and AGN (eg Kauffmann & Haehnelt 2000, Monaco, Salucci, & Danese 2000 and Haehnelt & Rees 1993) yet the direct comparison of galaxy and AGN luminosity functions can shed light on two fundamental properties of the black hole population: the fraction of massive black holes which are active, and their Eddington ratios. This is the subject of this paper.

Throughout we have taken $q_0 = 0$ and $H_0 = 100\ h$ km s^{-1}Mpc^{-1}.

2 METHOD

2.1 The relationship between galaxy and AGN luminosity functions

The luminosity function of AGN must be related to the mass function of massive black holes. If the masses of central black holes are related to the masses of their host galaxy bulges (Magorrian et al. 1998, Kormendy & Richstone 1995), then the luminosity functions of AGN and galaxies must be strongly related. This is modeled in the following formalism.

We define the luminosity function as

$$\phi = \frac{d^2N}{dV dL}$$

Where N is number of objects, V is comoving volume and L is luminosity. and start from the luminosity functions ϕ_i of galaxies of n different morphological types i. We assume that the spheroid components of galaxies of type i produce

Table 1. Schechter model galaxy luminosity functions from Folkes et al. (1999) and assumed fraction f_{sph} of B band light due to the spheroidal component.

Type	M^*_B	α	ϕ^*	f_{sph}
E/S0	-19.61	-0.74	9.0	0.7
Sab	-19.68	-0.86	3.9	0.25
Sbc	-19.38	-0.99	5.3	0.15
Scd	-19.00	-1.21	6.5	0.1
Sdm	-19.02	-1.73	2.1	0.02

a fraction of their light $f_{sph}(i)$. We can then translate from the ϕ_is to a spheroid luminosity function ϕ_{sph} by:

$$\phi_{sph}(L_{sph}) = \sum_{i=1}^{n} \frac{\phi_i(L_{sph}/f_{sph}(i))}{f_{sph}(i)}$$

We then obtain the mass function of spheroids by:

$$\frac{d^2N}{dVdM_{sph}} = \phi_{sph}\frac{dL_{sph}}{dM_{sph}}$$

and a black hole mass function Φ_{BH} is obtained using

$$\Phi_{BH} = \frac{d^2N}{dVdM_{BH}} = \int \frac{d^2N}{dVdM_{sph}} P(M_{BH} \mid M_{sph}) dM_{sph}$$

where $P(M_{BH} \mid M_{sph})$ is the distribution of nuclear black hole masses given spheroid mass M_{sph}.

Some fraction f_{AGN} of nuclear black holes are in an active (luminous) state and emit with luminosity L_{AGN}. Both L_{AGN} and f_{AGN} are likely to depend on M_{BH}. For simplicity we assume a functional relationship $L_{AGN} = F(M_{BH})$, although a distribution of luminosities $P(L_{AGN} \mid M_{BH})$ would be more realistic.

The AGN luminosity function ϕ_{AGN} is then:

$$\phi_{AGN} = f_{AGN}\Phi_{BH}\frac{dM_{BH}}{dL_{AGN}} \qquad (1)$$

It is appropriate to formulate the ratio of L_{AGN} to M_{BH} in terms of the Eddington ratio ϵ, the ratio of bolometric to Eddington luminosity $L_{\rm E} = 1.3 \times 10^{38}(M_{BH}/M)$ergs^{-1}.

$$\epsilon = \frac{L_{AGN}}{M_{BH}} \frac{M}{1.3 \times 10^{38}\text{erg s}^{-1}} \qquad (2)$$

3 CONSTRUCTING THE BLACK HOLE MASS FUNCTION

For the local galaxy luminosity functions we have chosen to use the recent determinations from the 2DF galaxy redshift survey (Folkes et al. 1999). This provides Schechter function model luminosity functions for 5 different spectroscopic classes of galaxy (corresponding to different morphological types) at $z < 0.2$. We have used values for f_{sph} (the fraction of B band light due to the spheroid component) based on the values given by Meisels & Ostriker (1984).

The model luminosity functions and spheroid fractions are listed in Table 1.

For the spheroid mass - to light ratio we use the best fit relation of Magorrian et al. (1998) for V:

$M/M = 0.097\ h\ (L/L)^{1.18}$

and assume B-V=0.9 for the spheroid component of all galaxy types (Pence 1976). For the black hole to spheroid mass distribution we use the best fit log-gaussian relation from Magorrian et al. (1998):

$$P(M_{BH} \mid M_{sph}) = \frac{f_{BH}\ e^{-0.5[\log(M_{BH}/M_S)-\log(x_0)]^2/\Delta^2}}{M_{BH}\Delta\sqrt{2\pi}\ \log_{\rm e}(10)}$$

where $\Delta = 0.51$, $f_{BH} = 0.97$ and $x_0 = 5.2 \times 10^{-3}$. We truncate this distribution at $\pm3\sigma$ because otherwise it predicts an unrealistically large population of very massive ($> 10^{11}M$) black holes.

The resultant black hole mass function is shown in Fig. 1.

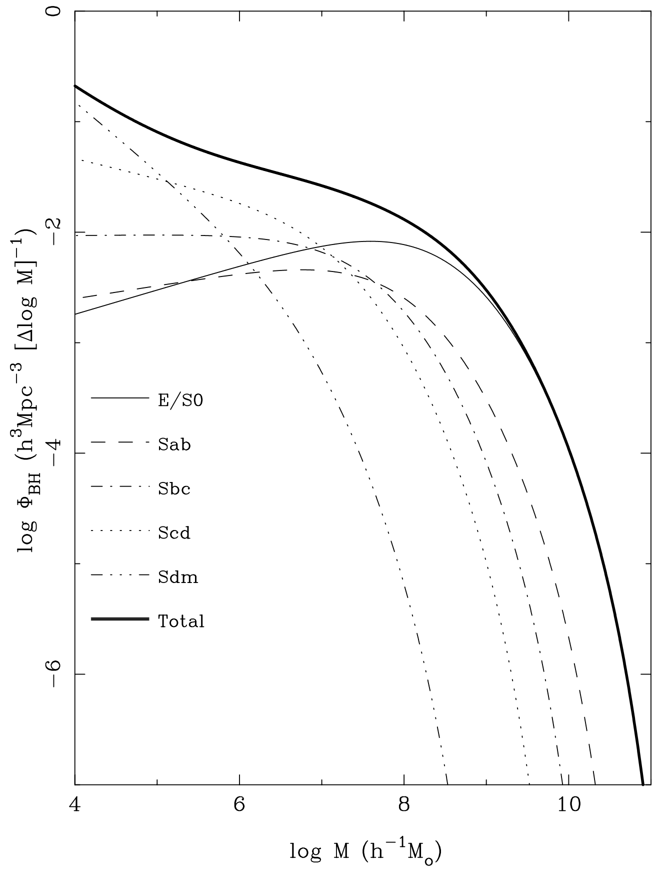

Figure 1. Mass function of black holes derived in Section 3.

4 FITTING THE ACCRETION RATE AND ACTIVE FRACTION

For the AGN luminosity function we have chosen to use the extended *Einstein* medium sensitivity survey (EMSS) X–ray selected sample (Stocke et al. 1991) restricted to type 1 (broad line) Seyferts with $z < 0.2$. X–ray selection is ideal because it is insensitive to the optical host galaxy properties. The restriction to broad line objects ensures that the sample contains only unobscured AGN for which the observed X–ray flux is a good measure of intrinsic luminosity, and the redshift restriction ensures that the sample is well matched to the 2DF galaxy sample and is without significant cosmological evolution.

The simplest relation between black hole mass and AGN luminosity (and therefore the starting point for this investigation) is obtained by assuming an Eddington ratio ϵ and an active fraction f_{AGN} independent of mass or galaxy type; this will be referred to as Model A henceforth.

Table 2. The nine closest galaxies from the EMSS Seyfert 1 sample, with their de Vaucouleurs (1959) morphological classifications as listed in the NASA Extragalactic Database (NED).

Source	$logL_X$	morphology
MS1215.9+3005	2.18	SB(s)a
MS0339.8-2124	2.30	SB(rs)a
MS0459.5+0327	2.59	E
MS1158.6-0323	2.45	E
MS2252.2+1126	2.00	Sab
MS1846.5-7857	2.08	SAB(r)b
MS1136.5+3413	2.74	SB0
MS0048.8+2907	2.96	SB(s)b

Since we are constructing an X–ray luminosity function rather than a bolometric luminosity function, and only considering type 1 Seyferts rather than all AGN, we replace f_{AGN} with f_{S1} and reformulate Equation 1 in terms of the Eddington ratio and include a bolometric correction β, where β is the ratio of the bolometric luminosity to the X–ray luminosity.

$$L_X = \frac{0.013\epsilon M_{BH}}{\beta} \qquad (3)$$

where L_X is the AGN 0.3-3.5 keV luminosity in units of 10^{40}ergs^{-1} and M_{BH} is in units of M.

$$\phi_X = \frac{d^2N}{dVdL_X} = \frac{f_{S1}\beta}{0.013\epsilon}\frac{d^2N}{dVdM_{BH}} \qquad (4)$$

We adopt $\beta = 20$ based on the mean type 1 AGN spectral energy distribution from Elvis et al. (1994).

A binned ($\Delta \log L = 0.3$) AGN X–ray luminosity function was computed from the EMSS sample (Fig. 2a) and compared to the model predicted luminosity function using the method described in Sections 2.3 and 5.2 of Page & Carrera (2000). Only luminosity bins containing > 10 objects were used in the fitting so that χ^2 could be used as a goodness of fit estimator; the resultant binned luminosity function uses 152 EMSS AGN.

A very good fit to the X–ray luminosity function of type 1 AGN is easily found. The best fit has $h\epsilon = 1.8 \pm 0.5 \times 10^{-3}$ and $f_{S1} = 7 \pm 2 \times 10^{-3}$ (where the errors define a box containing the 1σ, $\Delta\chi^2 = 2.3$, confidence interval) with an extremely low χ^2 of 0.4 for 6 fitted data points and 2 free parameters (i.e. 4 degrees of freedom, so $\chi^2/\nu = 0.1$). The best fit luminosity function is shown in Fig. 2a; the predicted luminosity function passes almost exactly through the data. Fig. 2b shows $\Delta\chi^2$ confidence contours on the fitted parameters.

However, despite the very good fit, there is a problem with this simple model. It is seen in Fig. 2a that the EMSS luminosity function is produced almost exclusively by E and S0 galaxies with only a small contribution from Sab galaxies at the low luminosity end, but it is well known that Seyferts are often spirals. Indeed, spirals are a significant component of the EMSS Seyfert sample itself; this is demonstrated in Table 2 which gives the morphologies of the nearest EMSS Seyferts.

To reproduce the the EMSS luminosity function with a mix of morphological types requires additional complexity in the model: to prevent early type galaxies completely dominating the luminosity function, f_{S1} and/or ϵ must depend on M_{BH} and/or galaxy morphology. Since different galaxy morphologies dominate the mass function at different masses, a direct dependency of f_{S1} or ϵ on M_{BH} results in an indirect dependency on morphology and vice-versa. If ϵ is to be varied it must be in such a way as to steepen the model luminosity function so that the relative contribution of E/S0 galaxies is reduced in the EMSS luminosity range. This means that more massive black holes (in E/S0 galaxies) must accrete with lower Eddington ratios than those of lower mass. If f_{S1} is to be varied it must be such that a smaller proportion of more massive black holes are actively accreting Seyferts than those of lower mass.

An ad-hoc example of one of these models is shown in Figs. 3a. In this model (hereafter Model B) we have assumed that the fraction of active Seyferts in E/S0 galaxies, and their Eddington ratios, are only half that of later type galaxies. Again, the best fit luminosity function is an extremely good fit with a χ^2 of 0.45, but this time the AGN luminosity function is produced by AGN with a more plausible mix of host galaxy morphologies. The fitted parameters are $f_{S1} = 7 \pm 3 \times 10^{-3}$ and $h\epsilon = 5 \pm 2 \times 10^{-3}$ for Sab and later galaxies (and by design half these values for E and S0 galaxies).

To obtain a conservative limit on the range of parameter space that brackets f_{S1} and ϵ, we have also considered the opposite extreme to the E/S0 dominated Model A: in Model C the active fraction of E and S0 galaxies is set to zero and they therefore make no contribution whatsoever to the AGN luminosity function. Since the fraction of Seyfert nuclei which are hosted by E and S0 galaxies is certainly between 0 and 1, it is reasonable to expect that the real values of f_{S1} and ϵ must lie somewhere between the acceptable values for Model A and Model C. The best fit AGN luminosity function and $\Delta\chi^2$ confidence contours for Model C are shown in Fig. 4.

5 DISCUSSION

The approach used here easily reproduces the shape of the AGN luminosity function; models A, B and C all have extremely low χ^2. The steepening of the AGN luminosity function from low to high luminosity is inherited from the black hole mass function, which in turn inherits the shape from the galaxy luminosity functions. Hence the shape of the AGN luminosity function ultimately derives from the same physical processes that give rise to the shapes of galaxy luminosity functions.

The fitted Seyfert 1 fraction in Sab and later type galaxies for Model B is $\sim 0.5 - 1\%$. This is quite a robust result: it isn't strongly affected by the contribution of E and S0 galaxies because Models A and C have very similar best fit values for f_{S1}. This compares well with the findings of optical emission line surveys of local galaxies. Maiolino & Rieke (1995), find that 5% of the revised Shapley-Ames catalogue of galaxies are Seyferts (with a Seyfert 1: Seyfert 2 ratio of 1:4 this corresponds to a Seyfert 1 fraction of 1%). Ho, Filippenko & Sargent (1997), find a Seyfert fraction which is twice that found by Maiolino & Rieke (1995), and therefore (assuming the Maiolino & Rieke Seyfert 1: Seyfert 2 ratio) about a factor two higher than would be expected from our value of f_{S1}. However, their Seyfert detection rate is high because their survey is sensitive to objects with very weak emission lines, which they term

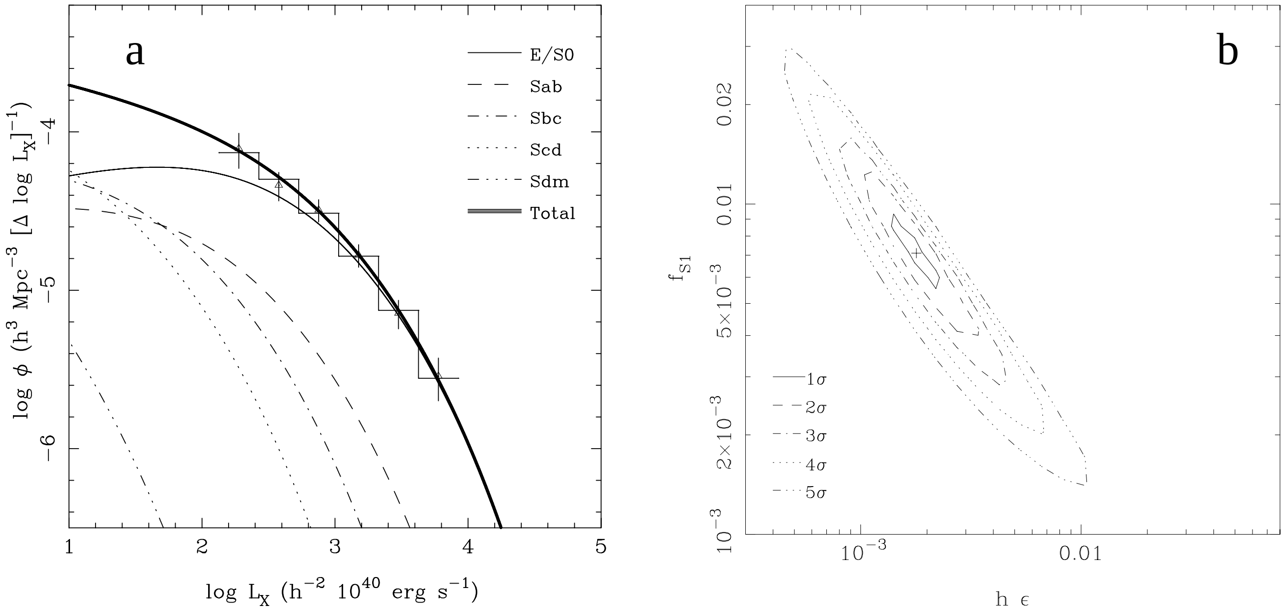

Figure 2. (a) X–ray luminosity function of the EMSS $z < 0.2$ AGN and best fit model assuming a universal Eddington ratio and a Seyfert 1 fraction f_{S1} which is independent of galaxy type or black hole mass (Model A). (b) χ^2 confidence contours for the values of Eddington ratio ϵ and active Seyfert 1 fraction f_{S1}.

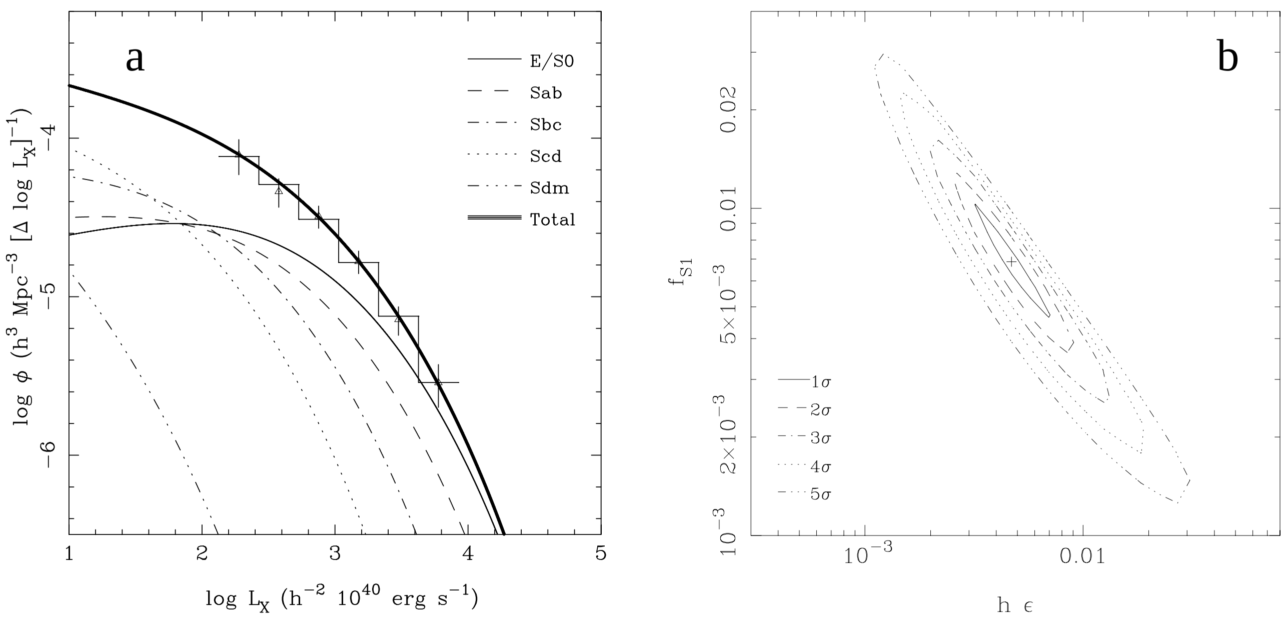

Figure 3. (a) X–ray luminosity function of the EMSS $z < 0.2$ AGN and best fit model in which the Seyfert 1 fraction of E and S0 galaxies is only half that in other types, and the Seyfert 1 nuclei hosted by E and S0 galaxies accrete with only half the Eddington ratio of Seyfert nuclei in later galaxy types (Model B). (b) χ^2 confidence contours for the values of Eddington ratio ϵ and Seyfert 1 fraction f_{S1} for Sab and later type galaxies in Model B.

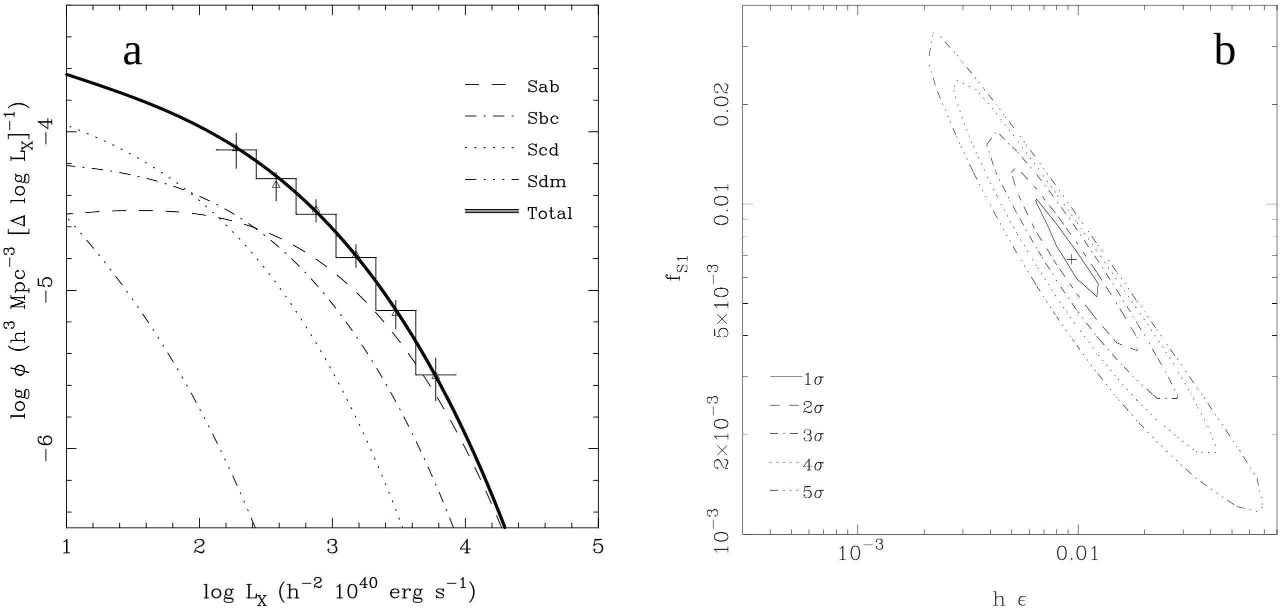

Figure 4. (a) X–ray luminosity function of the EMSS $z < 0.2$ AGN and best fit model in which E and S0 galaxies host no AGN (Model C). (b) χ^2 confidence contours for the values of Eddington ratio ϵ and Seyfert 1 fraction f_{S1} for Sab and later type galaxies in Model C.

"dwarf" Seyferts; it is not yet known whether these objects have the same X–ray properties as more luminous Seyferts which make up the EMSS sample. Both Maiolino & Rieke (1995) and Ho, Filippenko & Sargent (1997) find that the most common morphology for Seyfert galaxies is Sa - Sb further justifying our rejection of model A in Section 4.

In contrast to f_{S1}, the value of ϵ for typical Sab Seyfert galaxies depends quite strongly on the Seyfert activity in E and S0 galaxies. Taking the extremes of models A and C, a conservative conclusion is that $0.001 < \epsilon < 0.02$ for Seyfert nuclei in Sab galaxies. Our reasonable model B suggests $\epsilon \sim 0.005$ should be typical, considerably sub-Eddington and consistent with Seyfert activity occurring recurrently in a significant fraction of galaxies (model 'R' from Cavaliere & Padovani 1988). This is in good agreement with the predictions of recent models in which AGN, with lifetimes of order 10^7 years, are produced during the formation and merging of galaxies in a cold dark matter dominated Universe: Kauffmann & Haehnelt (2000) predict typical $\epsilon \sim 0.01$ while Haiman & Menou (2000) predict typical $\epsilon \sim 0.001$. Our results are also consistent with the range of Seyfert Eddington ratios given in the recent compilation by Wandel (1999). These lie between 0.001 and 1 and were obtained using a variety of different methods: broad line region kinematics, X–ray variability and modelling accretion disk spectra.

However, the range of acceptable ϵ is too low to be consistent with accretion disk models which have large outbursts. Siemiginowska & Elvis (1997) show that if AGN accretion disks are subject to the thermal-viscous instability driven by hydrogen ionization (Lin & Shields 1986) they are probably only observed in outburst, with typical $\epsilon \sim 0.1$. The study by Burderi, King & Szuszkiewicz (1998) concludes that if AGN have optically thick, geometrically thin accretion disks (Shakura & Sunyaev 1973) they almost certainly are subject to this kind of instability. The results presented here would therefore suggest that AGN are not fuelled by standard thin disks.

As explained in Section 4, the only way to get a plausible distribution of Seyfert host galaxies is to model the more massive black holes in early type galaxies with smaller values of ϵ, f_{S1} or both. Both these alternatives have important consequences for our understanding of AGN behaviour.

The first (ϵ smaller for more massive AGN) is intuitively reasonable because the early type galaxies which host more massive AGN contain less gas with which to feed them. However, it is contrary to the results of Wandel & Petrosian (1988) and Sun & Malkan (1989), who find from accretion disk modelling that luminous QSOs are both more massive, and accrete with higher Eddington ratios, than Seyfert galaxies (although this could be interpreted as a dependence of Eddington ratio on redshift rather than mass). The AGN evolution models of Kauffmann & Haehnelt (2000) and Salucci et al. (1999), also favour a situation in which the more luminous present epoch AGN are more massive *and* have higher Eddington ratios.

The second way to obtain reasonable Seyfert morphologies, by modelling a smaller Seyfert fraction f_{S1} for more massive black holes, is less controversial. For example, both Maiolino & Rieke (1995) and Ho, Filippenko & Sargent (1997) find that a higher fraction of Sa-Sb galaxies have Seyfert nuclei than E/S0 galaxies. In this case the mass function of active nuclei must be steeper than the mass function of inactive nuclei, unlike the simple recurrent activity models represented by model 'R' in figure 1 of Cavaliere & Padovani (1988).

This investigation can be substantially improved upon with a sample of X–ray selected Seyferts with optical morphologies; this would allow the matching of galaxy and AGN luminosity functions individually for each morphological type, providing a much more rigorous solution than our model B. This obviously requires a larger AGN sample than the EMSS one used here, for which the luminosity functions of different morphological types would be dominated by Poisson noise. We can expect that such a sample may soon be available from *ROSAT* All Sky Survey optical identification programmes.

6 ACKNOWLEDGMENTS

We would like to thank Jason Stevens, Francisco Carrera, Gavin Ramsay, Roberto Soria and Keith Mason for useful comments on the draft version of this paper.

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